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ABSTRACT

A discussion is provided of an instructional technique which has been used in a lower-division biology course to identify and clearly define critical thinking skills for students, model the skills, and give students frequent feedback by describing and evaluating what they are doing. Section I considers the links between the critical thinking and scientific processes. Section II describes the critical thinking skills that are emphasized in the course; i.e., description/definition, application, deduction and inference, and induction. Section III focuses on the use of the scientific process to teach critical thinking, defining and providing examples related to scientific hypotheses and conclusions, data analysis, the interpretation of results, and the construction and evaluation of models of the phenomena under study. Section IV considers ways in which critical thinking can be fostered by exams, offering examples of objective and essay exam questions. Finally, section V explores the role of the teacher in developing critical thinking. (LAL)

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TEACHING CRITICAL THINKING

USING THE SCIENTIFIC PROCESS AS A MODEL SYSTEM

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I. INTRODUCTION

The teaching examples given here have been used and refined for about ten years in a year-long lower division course for biology majors that includes 6 hours of lab each week in its schedule. The specific assignments are designed to require a lot of student time, class time, and teacher involvement, and therefore may not be appropriate for every kind of class. However the general concepts should be useful and it should be possible to tailor assignments to different levels and intents using these models for ideas.

The general plan is to identify and clearly define critical thinking skills for students, model them, and give students frequent feedback by describing what they are doing and evaluating it. For instance, the teacher can help students distinguish between CLARIFICATION of the hypothesis and ANALYSIS of it.

An important element of learning critical thinking is the development of an attitude to WANT to reason. To be willing to learn or to change perceptions as the result of reasoning requires some humility. The highest goal of reasoning processes is to discover "truth", or at least to increase understanding; it is NOT to vindicate oneself or prove oneself to be "right".

The Scientific Process is a method for evaluating observations and experiences in the world in order to discover underlying principles that govern nature. It is a strong-sense critical thinking process since the practitioner must ask such questions as:

Is the evidence sufficient to allow this conclusion?
Is this the only conclusion that this evidence supports?
Is the evidence reproducible and reliable?

II. CRITICAL THINKING SKILLS MOST ADDRESSED

The basic method used here is to describe the thinking skills being used as the teacher develops explanations for biological concepts. The list of tasks given here is not exhaustive, but is representative of the skills most needing description early in the process of modeling them for students.

A. Description/definition

Students often describe something by simply mentioning some aspect or characteristic of the thing. They need guidance and practice in producing FULL descriptions or definitions of phenomena.

A definition shows the full outline of an idea including its boundaries and sufficient information to distinguish it from closely related ideas. CLARIFICATION is often necessary in developing definitions.

For example, "morphogenesis" means a shape-changing movement of a group of cells, usually during development. This definition includes the information that a GROUP of cells must be involved (therefore it must be different from "differentiation"), and includes ALL shape changes (so that "invagination" is an example of morphogenesis and has a more narrow meaning).

B. Application

The difference between a general description of a rule or principle and an observation of that rule in action is sometimes elusive for students.

For example, "all organisms are made up of cells and cell products" is a rule; an application of this rule, that may not be obvious to students, is that BLOOD is composed of cells and cell products.

A process for deciding the relative evolutionary ages of two organisms or conditions could cautiously be given as follows: one compares the two and looks for features held in common and specialized features; the common features are usually older and the specialized ones younger. (Be careful! there are lots of exceptions to this--such as tape worms lacking a digestive tract by degeneracy not as a primitive condition!)

Now the rule can be applied to any new idea that arises:

(1) is mitosis older or younger than meiosis?
(2) is the haploid condition older or younger than the diploid condition?

Ask the students to apply it orally in class under supervision several times, then choose an unfamiliar example and have them apply it on an essay.

C. Deduction and inference

Several ideas can often be used together to produce a new one by logical connection. Students need to practice not only the skill, but also the checking of the result for logical and realistic consistency. (They often believe they have deduced impossible things!)

If the graph of rate of diffusion vs temperature is a direct proportion, one might be able to DEDUCE a role for brownian movement or for kinetic energy in the process of diffusion. Note that the motion of the molecules was not directly observed when data was collected.

One might be able to DEDUCE a pattern of inheritance for a locus from the results of several related genetics crosses.

Check the conclusions by looking to see whether predictions made by the deduced idea are fulfilled.

D. Induction

Scientists often use the process of induction when they observe several separate phenomena, then combine the observations into a single general statement. The general statement can become a theory or even, eventually, a natural law. It has broader application than any of the individual observations that led to its discovery, and leads to further predictions about the world.

Mendel observed that several characteristics in peas were inherited in regular mathematical ratios. He INDUCED the idea that inheritance was governed by some sort of physical unit that occurred in pairs and were separated in gametes. Not until gene sequencing methods became available in the 1970's was this idea demonstrated by physical evidence, but the rules and predictions that arose from his induction have been used heavily and to great benefit in the meantime.

III. THE SCIENTIFIC PROCESS AND CRITICAL THINKING

The scientific process is used to teach critical thinking in a REDUCTIONIST approach because
(1) the isolation of single steps in reasoning and
(2) the emphasis on using only measurable techniques
seem to provide fairly unambiguous examples of reasoning. As the student acquires more experience, less measureable examples will no doubt be added. Again the list of steps and the examples given are not exhaustive but are meant to stimulate ideas.

A. Hypotheses and conclusions

Hypothesis and conclusion statements are similar in both content and form. They should be clear statements that include the names of the variables studied and should describe the relationship between the variables that is the subject of the prediction or conclusion.

The reductionist approach used here emphasizes that the statement should contain only TWO variables each of which should be defined in a measurable way, and the relationship between the variables should also be measureable by graphical relationships or standard statistical means (e.g. Chi-square test or t-test).

Hypothesis and conclusions statements should be distinguished from the ISSUE under study. The issue is usually larger in scope and is frequently NOT accessible by simple experimentation. One task of the introduction section of a lab report is to connect the specific hypothesis being tested to the main issue.

EXAMPLES:

A poor hypothesis might say that "plants grow faster is brighter light". The term "grow" is not defined in a measureable way, "light" can mean a wider or narrower portion of the spectrum, and "faster" could imply any of several shapes of graph.

A better version of this hypothesis might be: "The change in leaf surface area in bean plants is directly proportional to the intensity of visible radiation to which they are exposed". With only minor additions in a Materials and Methods section, this already describes some of the main elements of the experimental method. Students who write hypotheses like these are thinking about the means of testing it during its composition.

A conclusion that says "the initial rate of an enzyme-catalyzed reaction is related to the concentration of substrate by a direct proportion that levels off at substrate concentrations that saturate the enzyme" leads to the expectation that one can predict the exact rate of reaction for known conditions in the test tube.

The version of the conclusion that says "adding substrate speeds up the rate of an enzyme-catalyzed reaction" leaves ambiguous the nature of the change in rate due to the added substrate.

B. Analysis

There are many steps in the analyis of data produced in an experiment, and the steps must be checked for logical consistence and for completeness.

1. Error analysis

Error is the variability that occurs in measurements. A particular measurement may vary from an exact representation of the thing being measured for a number of reasons:

a. inherent error
   Perhaps the system is inherently variable, such as heart rate in resting humans.
b. systematic error
   Perhaps the instrument or the method used was not entirely consistent.
   A special case of this might be improper use, or a MISTAKE.

Analysis must inquire how much intrinsic and systematic error is expected for the measurements of this experiment? Data points may be thought of as occupying a circle or oval with radii equal to the expected error magnitude.

Some points may have different error content than others (e.g. points read near 0.1 Abs on the spectrophotometer can be read to the nearest .001 Abs., while those near 1.0 can barely be read to the nearest .1 Abs. Different procedures might have been used for some points. A known mistake may have occurred in the collection of one point, or clear evidence of a mistake might be available.)

Error should be MEASURED (by distance from the expected position) and ACCOUNTED FOR by proposing a known or reasonable source for it. Error analysis can be checked by evaluating the consistency of evidence for error.

2. Interpretion of the results, or drawing the correct inferences about the relationship on the graph.

What shape graph is produced when the collected data points are plotted?

Is this the only graphical relationship that these points could be construed to produce?

Are all the data points that do NOT fall on the interpretation line clearly off the line because of ERROR (that is, fall within the error measured and accounted for in the first step) and NOT because the information does not fit the interpretation? (e.g. has the data been MIS-USED in the interpretation?).

How certain is the result shown? Are the samples measured representative of the phenomenon under study? Are the methods of measurement valid? Is significant information missing?

(These questions are asked in modified form if the chi-square or t-test is used).

3. Construction and Evaluation of Models of the phenomena under study.

The experimentor must connect the substance of the experiment to the scientific ISSUE being investigated.

What does this relationship between two specific, measurable variables have to do with the larger question of the experiment? Generally the larger question is not accessible by direct measurement, so the measured relationships have to be connected up by deduction or induction.

Are there causal relationships or explanations that lead to predictions that could be tested by further experiments?

Are there alternative conclusions or models possible from the known information?

Are there broader applications of the issue or the results to the world or to the investigator?

EXAMPLE: One might be interested in discovering which vitamins or minerals are important in the diet of snails, yet the experiment may explore only one or a small number of examples of nutrients, and the measurement of the effect on the snails might involve only some aspects of growth or health. The results obtained must be examined in the context of the larger question. Just how much was learned? How should the new information be applied in designing subsequent experiments? How reliable is the result for use in designing snail food? This is the means by which new details are integrated into the body of scientific knowledge.

IV. CRITICALLY THINKING ON EXAMS

A. Objective exam questions

Good objective questions that require students to think but don't set unintentional traps are difficult to write. Any question that is presented in the same context and couched in the same language as material covered in class or in the text is a recall or feedback question. A question only asks students to think if it presents a new task for them to complete.

Examples of thinking tasks for exam questions might be to ask a student to

APPLY a known concept to an unfamiliar case
COMPARE several familiar items to find some element of commonality or some distinguishing difference
DEDUCE a relationship from given relationships or from recalled knowledge
INDUCE a general concept from a known specific case

1. Recall questions:

Which organelle is primarily involved in the control of the cell?
a. mitochondrion
b. nucleus
c. chloroplast
d. nucleolus

Which of the following is surrounded by a double unit membrane?
a. mitochondrion
b. plastid
c. nucleus
d. all of these

2. Thinking questions: (providing the critical ideas have not been covered in class). Examples may be trivial or very difficult.

The steps in the dark reactions of photosynthesis are most similar to those in
a. glycolysis
b. the Kreb's cycle (COMPARE known steps)
c. oxidative phosphorylation
d. the light reactions

During the metamorphosis of a tadpole into a frog, the tail is lost. Which of the following would be most likely to be involved in this reabsorbtion of the tail?
a. nucleus
b. Golgi apparatus (APPLY known functions)
c. lysosome
d. mitochondrion

The process that has the opposite result from meiosis is
a. mitosis
b. oogenesis (COMPARE process in one
c. fertilization aspect--their result)
d. sporogenesis

Which of the following pairs is written in the correct evolutionary order (oldest-youngest)?
a. eucaryotic-procaryotic
b. meiosis-mitosis (APPLY a reasoning rule)
c. haploid-diploid
d. heterogamete-isogamete

The cells of ALL living things contain
a. organelles
b. nuclei (COMPARE to find a general
c. nucleic acid feature)
d. cell walls

Which of the following organelles is the largest?
a. mitochondria
b. chloroplasts (APPLY evidence from direct
c. lysosomes observations in the microscope
d. Golgi bodies and in electron micrographs)

B. Essay exam questions

Essay questions are easier to write and more difficult to grade than objective ones.

The question should ask a student to use a thinking task that has been modeled on a subject which should have been studied but in an example that has NOT been demonstrated.

The tasks are the same ones already described:
- describe or define
- distinguish between
- compare and contrast
- show how a specific experiment is related to a general conclusion
- induce a general principle to cover the following group of observations

Grading of these essays requires that the teacher describe in grading notes how the thinking task was or was not adequately addressed. Sometimes the knowledge of the student alone is the cause of a poor essay, but teachers must guard against giving top marks to papers that have solid knowledge but fail to exhibit good thinking skills. Only consistent grading and repeated explanations by the teacher will permit students to discover what these skills are and to be able to tell when they are using them.

EXAMPLES:

Compare Darwin's theory of evolution to Lamarck's and show how evidence available to you supports one theory better than the other.

Create a theory that would account for both the apparent similarities and the differences between llamas and camels.

(Provide data):
Show how the data obtained in some specific genetics crosses of <u>Drosophila</u> fit a particular pattern of inheritance. Be especially careful to account for DIFFERENCES between the expected pattern of inheritance and the observed data.

V. ROLE OF THE TEACHER

In order to teach critical thinking, the teacher must be self-consciously aware of the steps in the process and point out to students where different tasks or skills are being used.

The dissection of thinking processes into single steps and the grouping of steps into types of tasks is a reductionist approach, but seems to provide clear illustrations for students.

The teaching of thinking requires a constant listening posture on the part of the teacher (listening for process as well as content) and the ability to think on one's feet.

Thinking, practical problem solving and "common sense" are valuable skills that today's students seem particularly lacking.

Students retain information learned in the context of thinking tasks far, far longer than memorized lists--and can USE it, too!

To help students make even small improvements in these is rewarding and worthwhile.

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